Hand Exoskeleton to Assess Hand Spasticity

Citation for published version:
Erden, MS, McColl, W, Abassebay, D & Haldane, S 2020, Hand Exoskeleton to Assess Hand Spasticity. in *2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob).* International Conference for Biomedical Robotics and Biomechatronics, IEEE, pp. 1004-1009, 8th IEEE RAS/EMBS International Conference on Biomedical Robotics & Biomechatronics 2020, New York, New York, United States, 29/11/20. https://doi.org/10.1109/BioRob49111.2020.9224329

Digital Object Identifier (DOI):
10.1109/BioRob49111.2020.9224329

Link:
Link to publication record in Heriot-Watt Research Portal

Document Version:
Peer reviewed version

Published In:
2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)

Hand Exoskeleton to Assess Hand Spasticity

Mustafa Suphi Erden[1], *Member*, William McColl, Djouzar Abassebay, Shaun Haldane

***Abstract*— In this paper, a prototype exoskeleton is proposed to perform active finger movements to mimic a therapist for assessment of hand spasticity. Current methods for assessing spasticity are based on the subjective appreciation of physiotherapists as there is no quantifiably standardized method of evaluation and no rigorous method to record data for monitoring. For the purpose of imitating the therapist's movements and recording data pertaining spasticity, servos are used to manipulate each joint in an index finger in a programmable and controlled way. Film type force sensors are used at fingertip to judge the maximum opening and closing capability of the patient's hand in relation to the force which would be felt by a therapist due to the patient's resistance to passive movement. Using potentiometers and positional data from the servo motors the trajectory of the finger joints is recorded in parallel to the fingertip force applied during the movement. The exoskeleton is a three degrees of freedom system which can move the index finger through an entire range of motion. The physical prototype and the software control module have been tested to validate the functionality of the mechanical structure, measuring, and recording capabilities. A GUI software tool is designed to be user friendly for the medical therapists and to produce a report document in a style familiar to them. Positive feedback was obtained from medical therapists about this initial prototype.**

I. INTRODUCTION

In this study we present the development and initial tests with a hand exoskeleton prototype to be used for spasticity assessment (Fig. 1). The biological mechanisms behind spasticity are still not fully understood. A working definition that has been agreed on describes spasticity as a velocity-dependent increase in the resistance to imposed movement [1]. Spasticity is an extremely common symptom seen in many neurological conditions, including head or spinal cord injury, stroke, cerebral palsy, and multiple sclerosis [2]. It is used as a general term for symptoms such as clonus, hypertonus, hyperreflexia, abnormal motor patterns or even weakness [3]. Common treatment comprises a combination of physiotherapy and medication, yet modern therapy concepts aim to limit or abstain from medication to avoid by-effects such as constant fatigue, reduced cognitive ability or reduced motor skills [4]. Physiotherapy involves measures to both relax the affected muscles and strengthen them, making sure there are no long phases of inactivity as muscles deteriorate measurably after only a few days of immobility [5]. This highlights the importance of constant dynamic activity that significant improvement can be achieved only if the patient and/or the patient's family/carers carry out exercises at home on the affected limb joints [2]. Knowing precisely the severity of

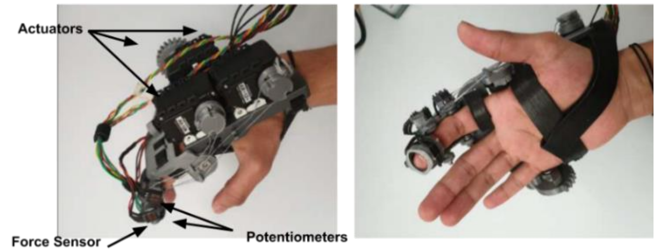

Fig. 1. Developed exoskeleton prototype for spasticity assessment.

spasticity of a patient could help doctors prescribe a proper treatment. According to [6], an early identification of the severity of symptoms and an adequate intervention to treat this pathology can minimise the development of long-term secondary complications, especially for children. Notwithstanding this lack of accuracy in the assessment, only a very few studies have addressed a valuable solution [7].

Spasticity is assessed to judge the requirements of the patient's rehabilitation program as well as to evaluate their progress and is usually done in a rehabilitation facility. One method of evaluation is the Ashworth Scale, which measures the quality of muscle reaction to passive movement at the shoulder, elbow and wrist [8]. Bohannon and Smith [9] improved the original Ashworth Scale by adding a new grade to the system. However, despite this adaptation Ashworth Scale did not prove to be sufficiently reliable with results being only around 63% accurate in [10]. Consequently, the Tardieu Scale, which was originally introduced in 1950s by G. Tardieu, was revisited and showed results of 94-100% accuracy in the same study [10]. The Tardieu Scale was improved further into Modified Tardieu Scale by Mehrholz et al. [11] by taking into account measurements of the muscle response at three different velocities. The Procedure of (Modified) Tardieu Assessment is schematically described in Fig. 2.

Despite the high accuracy of the Tardieu Scale, this measurement system also shares, as the others, the risk of inaccuracy, as they all involve subjective judgement by a therapist. Even when carried out by experienced therapists, the point at which they draw the line between any two categories of level of severity of the condition might vary. A hand-exoskeleton device that gathers the hand motion and force data could enable an objective use of the Tardieu Scale to achieve a more precise and robust assessment.

An overview of hand exoskeletons for assistance and rehabilitation purposes can be found in [12], [13], [14]. The majority of these exoskeletons enhance the patient's active grip as this is often not strong enough for lifting objects or

* This work has been supported by EPSRC grants EP/F500385/1, EP/H1012338/1, EP/M025594/1, EP/M025977/1, EP/L016834/1 and BB/F529254/1. This work has been performed at Heriot Watt University under the program of Centre for Doctoral Training for Robotics and Autonomous Systems under Edinburgh Centre for Robotics.

[1] M.S. Erden and W. McColl are; D. Abassebay and S. Haldane were with the School of Engineering and Physical Sciences, Heriot-Watt University, UK (e-mail: m.s.erden@hw.ac.uk; wm70@hw.ac.uk; da65@hw.ac.uk; shaun.haldane@googlemail.com). M.S. Erden and W. McColl are also with Edinburgh Centre for Robotics.

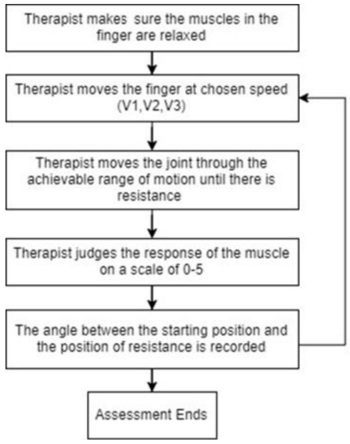

Fig. 2. Procedure of (Modified) Tardieu Assessment

operating assistive equipment. However, this requires the patient to already have a certain level of control in the arm muscles as well as the cognitive ability to understand and carry out tasks. Further, it is often necessary for the patient to be able to sit or stand in a certain position as the exoskeleton is attached to an immobile apparatus, such as with the Armeo series by Hocoma [15].

A device to assess spasticity must mimic the same movements a physiotherapist applies on a patient's hand, without any active action by the patient and must follow a confirmed procedure such as the Tardieu Scale Assessment. These movements are basically based on stretching the limb to enhance flexibility and doing this motion repetitively to improve elasticity [16], [17]. In this study we develop an exoskeleton device along these lines that can be used for assessment and potentially also for therapy of spasticity. The device we propose (Fig. 1) is simple enough to be low cost and portable, enabling in-house usage, yet effective to fulfil the functions of a therapist as the design closely follows the requirements of the state-of-art therapy practices.

II. Design Criteria

Contact force at the fingertip has been understood to be the most reliable method for controlling grasping force [16], [17], [18], which relates to the power of the motors to be used in an exoskeleton as in this study. For measurement of the contact force, force sensing resistors (FSRs), pneumatic pressure sensors, and strain gauge sensors are predominantly used [18]. The middle finger was shown to exert the greatest force while gripping: a maximum grip force of 80 N was measured between the middle fingertip and a suspension rope while holding a 3.5 kg weight suspended by a rope [19], [20]. For the design of the exoskeleton in this study, this level is an indicator for an upper limit on the power of the motors to be used, however a lower limit would be desirable as such high force might be unsafe for a patient with limited muscle capability. In order to determine the maximum point of opening of a limb a force sensor needs to be attached to detect resistance to the movement, as some patients have limited sensory capacity and would not be able to recognise and tell such limit points themselves, which might lead to mild injuries [21]. This force sensor serves as the basis for using the exoskeleton as a measurement device because it determines the range of motion with a certain contact force, similar to how the traditional assessment uses the contact force between the patient's hand and the therapist's hand to judge the joint limits. For an accurate assessment, specifically when using the Tardieu Scale, it is essential that the angles of the joints are accurately measured throughout each procedure. After a few initial prototypes and consultation to the medical therapists, the following design specifications were identified for and met with the current prototype robotic hand exoskeleton:

1) Focusing on the opening and closing movement of the *index finger* as a first step.
2) Having sufficient degrees-of-freedom to replicate the same movements of a physiotherapist/doctor; therefore, *three degrees-of-freedom controllability* is required for the index finger around the three finger joints; rather than an under-actuated system with a synergetic movement of the three joints that could be realized with a single motor.
3) *Lightweight and portable* design.
4) Fitting an *average-size man hand*, rather than targeting an adjustable hand to all sizes (therefore, *another version for women and for children* should be developed afterwards).
5) Having a *full range of motion* to reach the nominal full hand opening and closing capabilities.
6) Fitted with *two force-sensors*, one on dorsal and one on the ventral of the fingertip in order to monitor the tension of the finger in both directions of movement.
7) Fitted with *potentiometers* along the joints to accurately record the joint angles; rather than relying on the motor readings for these joints.
8) The control system should be *adaptable* by the therapist to the condition of each patient, i.e. the (maximum) velocity and the (maximum) force range can be adjusted according to the patient's status.
9) Having *powerful enough actuation* to pull the hand to the maximum range of motion and hold for a desired time.
10) Being *comfortable* to wear.
11) Provision of *safety solutions to minimise the risks* of danger and injury to the patient.
12) Provision of an easy to interpret record of data for assessment by the doctors, in a style they are used to.

III. Development and Implementation

In order to mimic a therapist's procedure of assessment of spasticity, a control system was created to actuate the motors and monitor the contact force between the patient and the exoskeleton, so that the motors are stopped once a threshold force is achieved.

A. Control Concept

Tardieu Scale Assessment consists of the evaluation of two parameters: the *quality* of muscle reaction and the *joint angles* corresponding to the limits of movement range. Traditionally, quality is measured with the appreciation of the specialist and joint angles are measured with a goniometer. The maximum joint angle is recorded at three different speeds: as slow as possible (V1), while the limb segment is falling freely under gravity (V2), and as fast as possible (V3). The valuation is always performed with the same hand/arm posture. By moving the patient's finger at a speed V1, the maximum range of movement can be identified and recorded to be used in the assessments with the other two speeds.

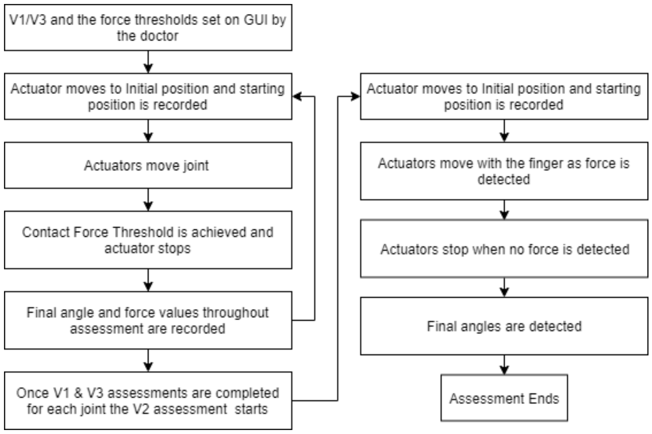

Fig. 3. Workflow of operation of the exoskeleton to mimic the procedure of Modified Tardieu Assessment.

The system first moves to the closed hand position and then, as schematically described in Fig. 3, the actuator controlling one of the three joints extends the joint at a constant speed. The value from the force sensor is monitored throughout the movement and if the force threshold is reached, the actuator stops, and the final joint angle is recorded as a limit on the range of the movement. The actuator then resets to its original position, ready for the assessment of the next joint. This procedure is followed for the proximal interphalangeal (PIP), distal interphalangeal (DIP), and metacarpophalangeal (MCP) joints. Fig. 4 gives a schema of the overall control system to operate the exoskeleton.

B. *Graphical user Interface (GUI)*

The aim of the GUI was to create a software that could collect and analyse data and that would be intuitive for a doctor to work straight away with little training. For real-time monitoring by the doctor, it was necessary that the sensory data would be displayed in real time during the assessment. The force thresholds used to identify the ranges of movement and the velocity that is proper to be applied on the joints need to be set by the doctor depending on the status of the patient. In other words, the values V1, V2, and V3 should be identified and pre-set by the doctor. Therefore, the user needs to easily change the speed values and force thresholds for the tests. The GUI in Fig. 5 was designed and developed to accompany the hand exoskeleton for these purposes. The following features were included in the GUI:

- Activation of the exoskeleton for assessment in the three velocities (slow, under gravity and as fast as possible) mimicking the Tardieu Scale;
- Depicting the force sensor and joint angle data in real-time;
- Allowing inputs for force and velocity values as well as maximum joint angles to avoid hyperextension;
- Printing and plotting the force and joint angle values on an output file for assessment by the therapist (not presented in this paper due to the page limits) and saving the collected data and the file.

C. *Electronic and Mechanical Components*

The exoskeleton is composed of three Dynamixel AX-12A servo actuators (Fig. 1). This motor is widely used in robotic applications as it is compatible with Robot Operating System (ROS) communication and designed to publish the speed, temperature, torque, position, and other useful parameters into ROS in real time. For our application, a 15.3 kg/cm of torque as rated for this motor was enough to actuate the finger joints and also not too high so that the finger cannot be damaged in case of any control errors.

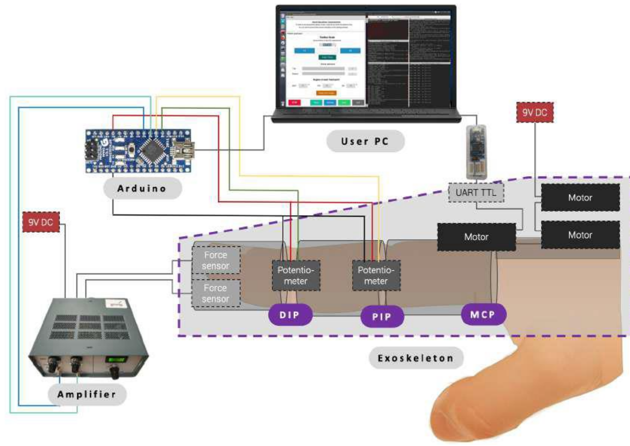

Fig. 4. Simplified schema of overall control system to operate the exoskeleton.

An Arduino Nano microcontroller was used to record data from the potentiometers on the joints and from the force sensors at the fingertip, in real time. The microcontroller took sensor readings as analogue inputs and sent to the controlling laptop a digital data package with all the sensors values via the Serial port. Torque and speed data were recorded by the controlling laptop directly from the actuators via TTL to USB connection. The laptop controlled the motors through a UART module (universally asynchronous receiver/transmitter).

Two force sensors (FSS1500NSB) have been used at the ventral floor and dorsal roof of the tip of the index finger to record the force applied by the fingertip during the assessment. A calibration was performed to ensure that the force readings were accurate and consistent across both sensors. Two potentiometers have been used to accurately measure the DIP and PIP joint angles. The MCP joint angle is directly computed using the motor angle. The potentiometers have a total

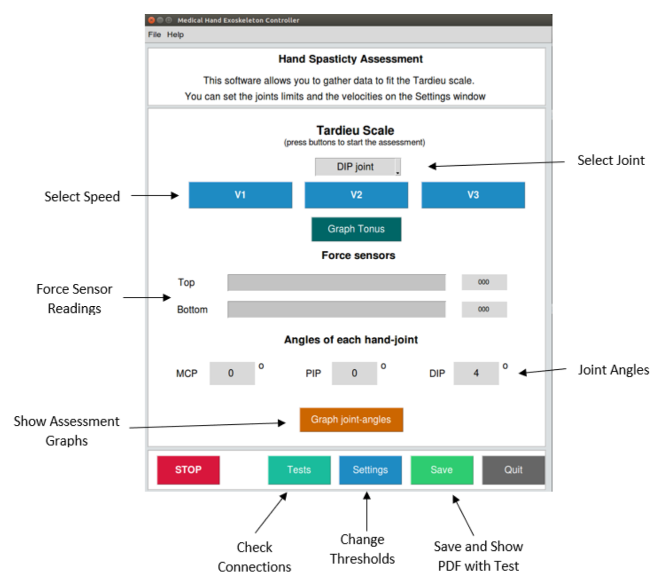

Fig. 5. GUI used to operate the exoskeleton in different modes of assessment.

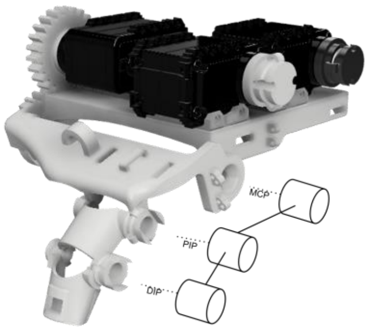

Fig. 6. CAD drawing of the hand exoskeleton with the three actuation joints.

rotational angle of 300 degrees and a low rotational torque of 1 to 8 Nm, indicating an insignificant friction.

To ensure that the system was lightweight and portable a tendon driven mechanism was chosen to activate the PIP and DIP joints, which are distantly located from the motors. The system was designed in a way that each joint could be activated in both directions with one motor per joint. A spur gear actuation was preferred for the MCP joint as, unlike the other two joints, it was practically possible in design and as its position accuracy is better compared to a tendon driven mechanism. However, unlike the PIP and DIP, the MCP joint of each finger is difficult to be isolated from that of the other fingers, due to the lack of access to the joint from at least one side. Therefore, the spur gear actuation was designed to manipulate all knuckle joints together (all four MCP joints on four fingers). The gears were 3D-printed with high density to increase the robustness. The CAD model of the exoskeleton with the motors actuating the three joints is given in Fig. 6.

Several features were incorporated to ensure that no damage would happen to the finger during assessment. Joint limits can be set in the GUI so that the hand will not move once any of the potentiometers reaches the threshold. Physical stops have been added to limit the range of motion of each joint to standard hand movement ranges: 110 degree for both the MCP and PIP joints and 100 degrees for the DIP joint. The overall system was equipped with a standard emergency button (not shown in this paper) to cut out all the power to the system in case of any failure and/or undesired system behaviour.

The final version of the exoskeleton in Fig. 1 is created for a man with an average hand size (189 millimetres by 84 millimetres). To secure the device to the patient's hand, three straps are used with hook and loop fastening, which was a practical solution for easy and comfortable wearing. A small strap between the MCP and DIP joints is attached to prevent any detached movement of the finger from the exoskeleton. In this way it was ensured that the three joints of the index finger coincide with the three corresponding joints of the exoskeleton. The lateral movement of the finger is neglected as the MCP joints of four fingers are moving all together.

IV. Testing Functionality

To test the functionality of the prototype a mock experiment was performed with a healthy subject (one of the authors). The subject did not have any known hand condition. During the assessment, the arm and palm were rested on a table to negate the weight of the exoskeleton and the subject was not resisting the movements of the exoskeleton. The position of the arm was in such a way to avoid any undesired tension during the assessment. The steps of the procedure are:

1) Rest the arm of the subject.
2) Create a new assessment file in GUI with the name of the subject.
3) Start with V1 assessment for DIP, PIP and MCP joints that will identify the range of motion to be used in V3 assessment; plot both force sensor and joint angle values after each assessment.
4) Continue with V2 to see if the finger moves freely under gravity; plot both force sensor and joint angle values.
5) Continue with V3 assessment for DIP, PIP and MCP joints, plot both force sensor and joint angle values.
6) Finish by saving the assessment, in other words saving all the recorded data into an output pdf file.

The mock experiment was planned so that it mimicked a certain limit of angle for each joint before the full range of motion was achieved. These were realized during the experiment just by holding the finger at these joint limits. These angles were then measured in advance as a control, to confirm whether the exoskeleton could detect them accurately.

A. V1 Assessments

The V1 assessment aims to identify the maximum range of motion for each joint at a slow controlled velocity. It is done at constant speed with a PID controller at the start (acceleration) and the end (deceleration) of the movement. The motor's constant speed-facility is used in between these start and end movements. The first joint assessed is the DIP. The time that the trigger is reached using the pre-set force threshold (1.2 N) is shown for the DIP joint in Fig. 7 (a,b). The motor (blue plot) stops and rotates back to its initial position after recording the joint angle corresponding to the trigger instant. The joint angle and tip force recording of V1 assessment for PIP joint are shown in Fig. 7 (c,d). The V1 assessment for PIP joint is more complex than the previous one because in this case the DIP joint must be released to be free synchronously with the actuation of the PIP joint, in order to achieve a natural PIP movement. The threshold is also set to 1.2 N and a 2 second delay is set between the forward and backward movements. The third and final V1 assessment, for MCP, involves releasing the PIP and DIP motors to free motion synchronously with the MCP. We can see in Fig. 7 (e) that the DIP and PIP joints fluctuate but stay very close to zero.

B. V2 Assessments

Unlike V1 and V3, V2 assessment requires a single movement to detect the force, speed and final joint positions of a finger in a relaxed and passive motion due to gravity. This is a more complex assessment as it requires reacting as quickly as possible to the movement of the finger as it falls. To do this we move each of the joints downwards at the same rate as far as force above a pre-set and low-level threshold is detected on the ventral floor force sensor. Once no force is detected on the ventral sensor, we conclude that the finger has reached its final relaxed position (no pressing with the fingertip) and record the joint positions. The exoskeleton holds the finger at that position for eight seconds and then returns to the starting position. The plots for V2 assessment are given in Fig. 8.

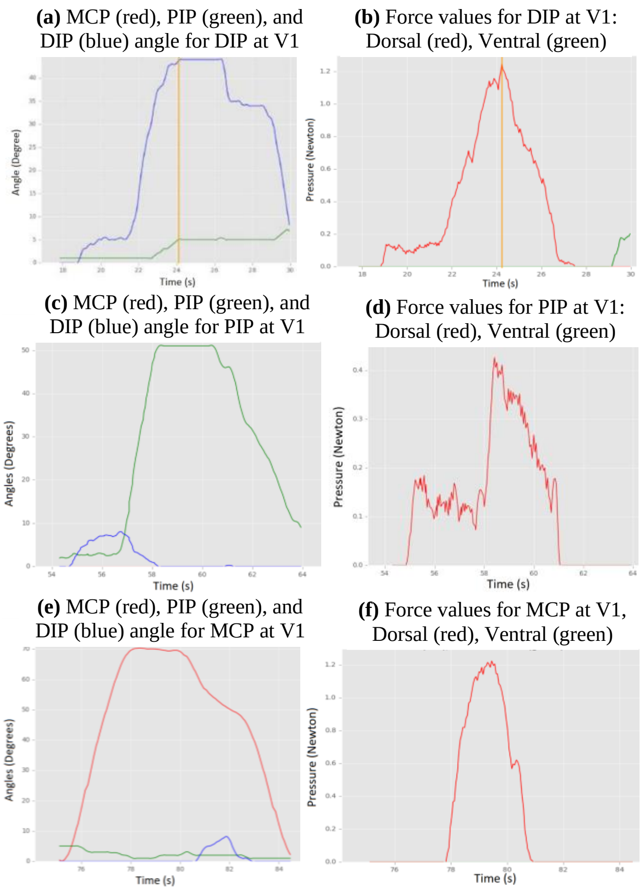

Fig. 7: Joint angle (left column) and force sensor (right column) values during V1 test for DIP (a,b), PIP (c,d), and MCP (e,f) joints.

C. V3 Assessments

V1 assessment provides the maximum range of motion for each joint and in V3 assessment, a fast movement is realized within these ranges. The aim is to detect a *catch* (resistance to movement) or a *clonus* (vibratory movement in both directions) at a certain angle during a quick stretch. Each joint is assessed separately with the results in Fig. 9. The full movement for each joint is realized in less than four seconds (whereas at V1 it was almost ten seconds). Please note that in these figures there is no evidence of a clonus because we experimented with a healthy subject with no hand disorder. A clonus would be represented as a rapid change of force signals due to oscillatory movement in between the dorsal and ventral sensors. However, a catch of resistance to the movement can be seen clearly at a timestamp of 171.5 seconds with the PIP measures and at 231.8 seconds with MCP measures in Fig. 9 (c) and (e), respectively, with the corresponding resistive forces of 0.75 N and 0.5 N for PIP and MCP, respectively. We do not observe such a clear catch for the DIP joint in Fig. 9 (a).

D. Discussion

With a mock-up assessment experiment with a healthy subject, we have demonstrated the functionality of the exoskeleton as well as the utility of the GUI to perform the movements and record the essential data required for an assessment according to the Tardieu Scale. The prototype was able to perform assessments at different speeds on each of the three joints. Sufficient amount of force could be applied to open the subject's hand to its full range and take a recording

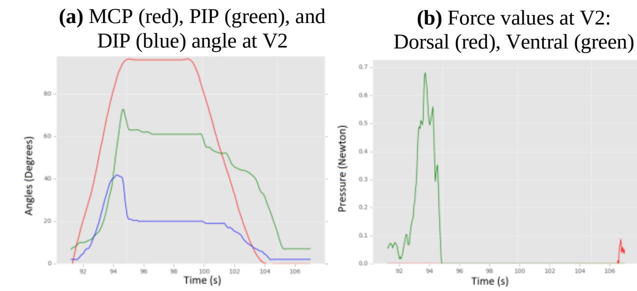

Fig. 8: Joint angle (a) and force sensor (b) values during V2 test.

of position. The motors would stall if further force was commanded by the software, which acts as a safety feature.

The experiments show that clear joint limits could be found using this system. Once the force values were reached the motors would immediately stop and the joint positions at that point could be recorded. Although it was not possible at this stage to verify detection of a clonus (as we did not experiment with subjects with spasticity), the groundwork is in place to be able to do this as the system records and depicts (in real-time) the required data for such detection. By using potentiometers parallel to the two furthermost joints in the finger and by directly actuating the MCP joint with gears, accurate and timely positional data could be acquired. This data alongside the force data at the fingertip are the key elements when assessing a patient with spasticity. The motors could be activated properly using a velocity and position based controller.

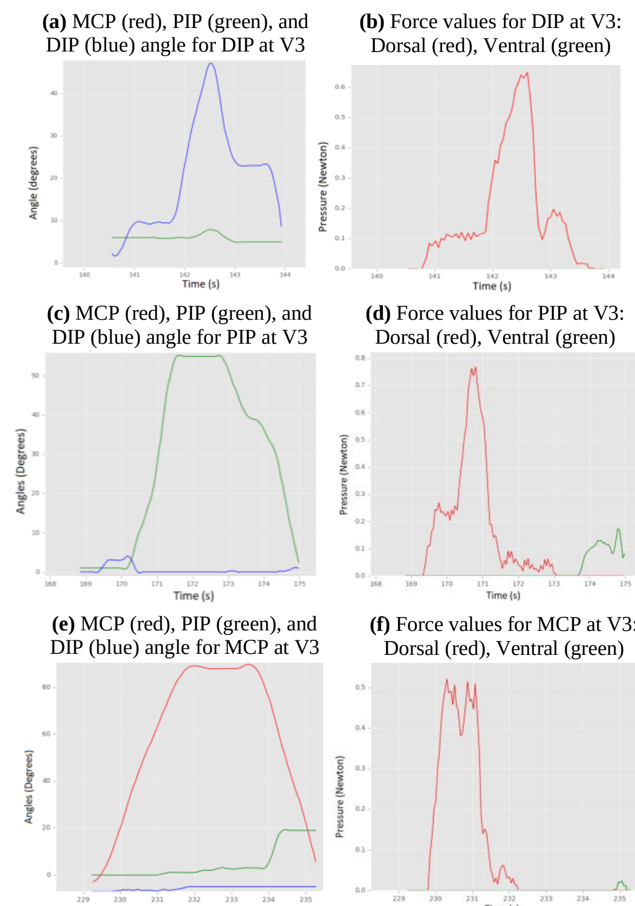

Fig. 9: Joint angle (left column) and force sensor (right column) values during V3 test for DIP (a,b), PIP (c,d), and MCP (e,f) joints.

One of the requirements for the hand exoskeleton was to make its use relatively simple and straightforward for medical therapists. This was for setting the angular velocities and force thresholds and selecting among the different modalities of measurements, and finally producing a document depicting all the measurements in a systematic way for an easy diagnosis by the medical therapist. The GUI targeted these as a user-friendly interface between the therapist and the electronic controllers of the exoskeleton. We have demonstrated the GUI and its output files to medical therapists[2] and received confirmation that the prototype GUI had the required features necessary to assess a patient. They mentioned that it was flexible so that each joint could be separately examined, which would be useful if only certain joints were affected, and also because a specific sub-assessment could be selected rather than just running through an entire assessment.

This prototype is promising for development of an exoskeleton as an automatic assessor and therapy device to quantify and monitor the progress of the passive range of motion achievable by a patient. It serves as a basis for further research and development, which would include designing similar prototypes for the other fingers as well as a prototype which would be fitted to all fingers. Further improvements could be made by adding extra force sensors to ventral and dorsal surfaces of each finger link. This would help make the assessments on the PIP and MCP joints more accurate. We also envisage that the system can be embedded with machine intelligence trained with data of real-patient assessments, in order to output automated assessment conclusions without the need for a doctor to process the raw sensory data.

A limitation with the current design is that patients suffering from severe spasticity would not be able to use it due to the lack of any movement in their hand. The exoskeleton would therefore be rather useful as an early assessment and diagnosis device and as a device to monitor the change in a patient's condition. The doctors we have spoken to have stated that it would be better to have an actuated wrist joint when performing the assessments, which is not currently met but could easily be achieved with some modifications to the design. Finally, Dr Wee Lam has commented on the benefits of such a device particularly for monitoring and assessing the hands of children, as rehabilitation is more common and effective with young patients.

E. Conclusion

In this study we developed a prototype of a low-cost and practical exoskeleton device for assessment and therapy of spasticity. With spasticity still not being completely comprehended but being researched intensively, quantified assessment and therapy devices would support our understanding an d treatment of spasticity. Most importantly, a device as proposed in this study would provide an objective method of assessing the changes in spasticity after a patient received treatment. Furthermore, with some modifications of its control algorithms, this exoskeleton has also the potential to be used as a device for rehabilitation.

References

[1] J. Lance, "The Control of Muscle Tone, Reflexes and Movement: Robert Wartenberg Lecture," *Neurology,* vol. 30, pp. 1303-1313, 1980.

[2] V. L. Stevenson,, L. Jarett and L. Eds, "What is spasticity," in Spasticity Management: A Practical Multidisciplinary Guide.," *Informa Healthcare*, p. 3, 2006.

[3] J. Mehrholz, "Physical Therapy for the Stroke Patient. Early Stage Rehabilitation," *Stuttgart: Georg Thieme* , pp. 58-59, 2012.

[4] A. Naro, A. Leo, M. Russo, C. Casella, A. Budo, A. Crespantini, B. Porcari, L. Carioti, L. Billeri, A. Bramanti, P. Bramanti and R. Calabro, "Breakthroughs in the spasticity management: Are nonpharmacological treatments the future?," *Journal of clinical Neuroscience,* vol. 39, pp. 16-27, 2017.

[5] S. M. Parry and Z. A. Puthucheary, "The impact of extended bed rest on the musculoskeletal system in the critical care environment," *Extreme Physiology and Medicine,,* 2015.

[6] A. Thompson, L. Jarrett, L. Lockley, J. Marsden and V. Stevenson, "Clinical management of spasticity," *J Neurol Neurosurg Psychiatry,* vol. 76, no. 4, pp. 459-63, 2005.

[7] L. P. Cavorzin and et al, "Evaluation of pendulum testing of spasticity," *Journal of neuroengineering and rehabilitation,* vol. 45, pp. 510-516, 2002.

[8] B. Ashworth, "Preliminary trial of carisoprodol in multiple sclerosis," *Practitioner,* vol. 192, pp. 540-542, 1963.

[9] R. W. Bohannon and M. B. Smith, "Interrater reliability of a modified Ashworth Scale of muscle spasticity," *Physical Therapy,* vol. 67, pp. 206-207, 1987.

[10] L. Patrick and L. Ada, "The Tardieu Scale differentiates contracture rom spasticity whereas the Ashworth Scale is confounded by it," *Clinical Rehabilitation,* pp. 173 - 182, 2006.

[11] J. Merholz and et al, "Reliability of the Modified Tardieu Scale and the Modified Ashworth Scale in adult patient with severe brain injury: a compassion study," *Clinical Rehabilitation,* vol. 19, pp. 751-759, 2005.

[12] A. Chin and et al, "Mechatronic Design and Characterization of the Index Finger Module of a Hand Exoskeleton for Post-Stroke Rehabilitation," *IEEE/ASME Transactions on Mechatronics,,* pp. 884-894, 2012.

[13] S. Guo and et al, "Soft Actuator for Hand Rehabilitation," in *International Conference on Mechatronics and Automation (ICMA),* Beiging, China, 2015.

[14] P. Ben-Tzvi, J. Danoff and Z. Ma, "The Design Evolution of a Sensing and Force-Feedback Exoskeleton Robotic Glove for Hand Rehabilitation Application," *Journal of Mechanisms and Robotics* , vol. 8, pp. 1-9, 2016.

[15] Hocoma, "Armeo Therapy Concept [online], available: https://www.hocoma.com/solutions/arm-hand/," 2017.

[16] S. Pauli and G. Leimer, "Ergotherapeutische Übungen in der handtheraphie," in *Loer Druck,* Dortmund, 2015.

[17] J. Sachse, "Extremitätengelenke. Manuelle Untersuchung und Mobilisationsbehandlung für Ärzte und Physiotherapeuten," in *Urban and Fischer,* Munchen, 2005.

[18] P. Heo and et al, "Current Hand Exoskeleton Technologies for Rehabilitation and Assistive Engineering," *International Journal of Precision Engineering and Manufacturing,* pp. 807 - 824, 2012.

[19] I. Jo, I. Bae and J. Bae, ""Design and Control of a Wearable and Force-Controllable Hand Exoskeleton System," *mechatronics,* vol. 4, pp. 90-101, 2016.

[20] J. Iqbal, N. G. Tsagarakis and D. G. Cadwell, "A Multi-DOF Robotic Exoskeleton Interface for Hand Motion Assistance," in *Annual International Conference of the IEEE Engineering in Medicine and Biology Science*, Boston, 2011.

[21] V. Mountcastle, "The Sensory Hand. Neural Mechanisms of Somatic Sensation," in *harvard University Press,* Cambridge, 2005.

[2] The authors thank Dr Alyson Nelson of Astley Ainslie Hospital in Edinburgh, Dr. Philippa Rust and Dr. Wee Leon Lam of St John's Hospital in Livingston and of University of Edinburgh, for their time, discussions, and valuable feedback on our hand exoskeleton and the GUI.